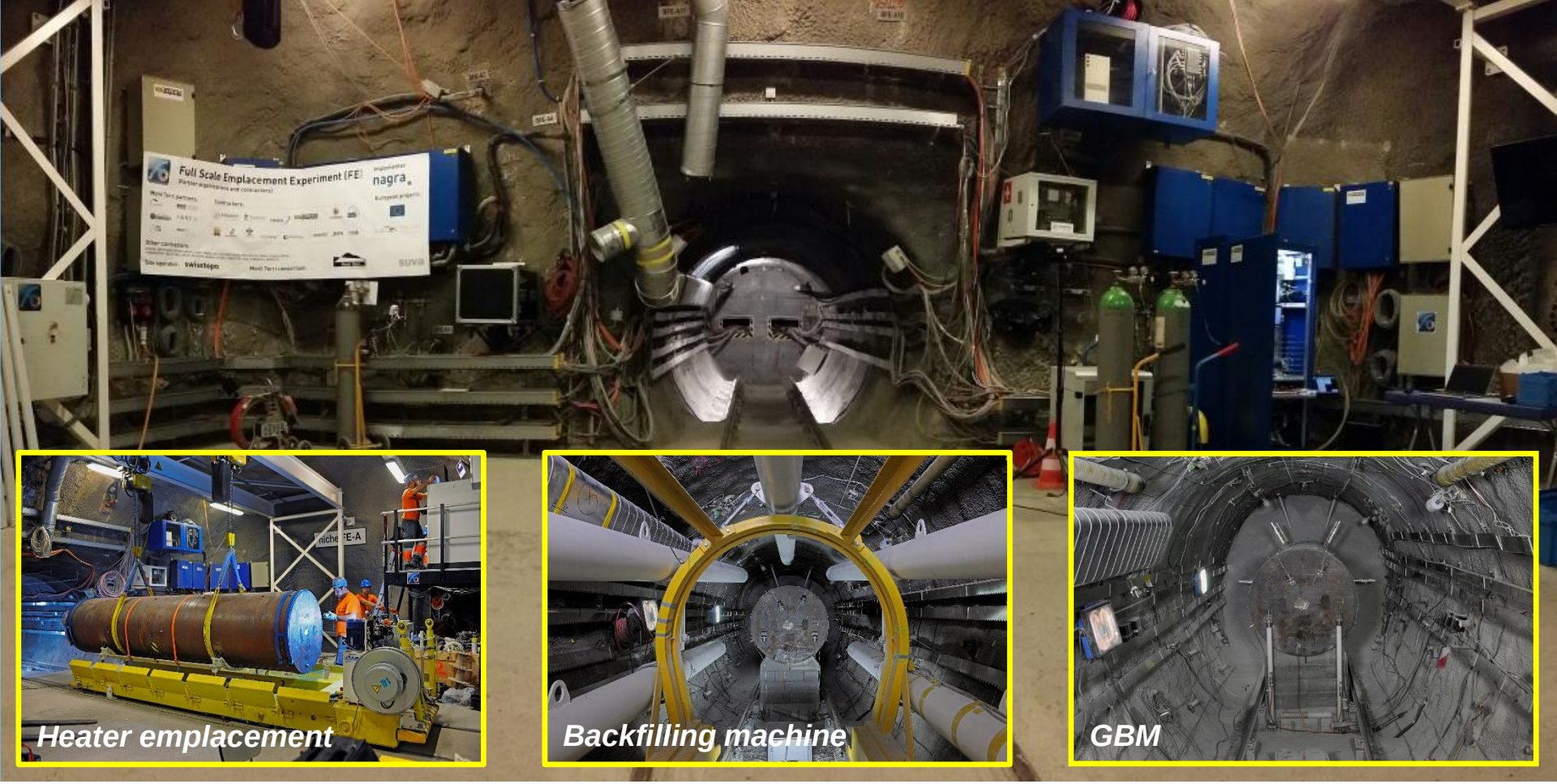

Heater emplacement

Backfilling machine

GBM

FE modelling Task Force and current status of data collection

A. Alcolea, B. Garitte, P. Marschall, B. Firat-Lüthi

Mont Terri TM-37, February 5th, 2019

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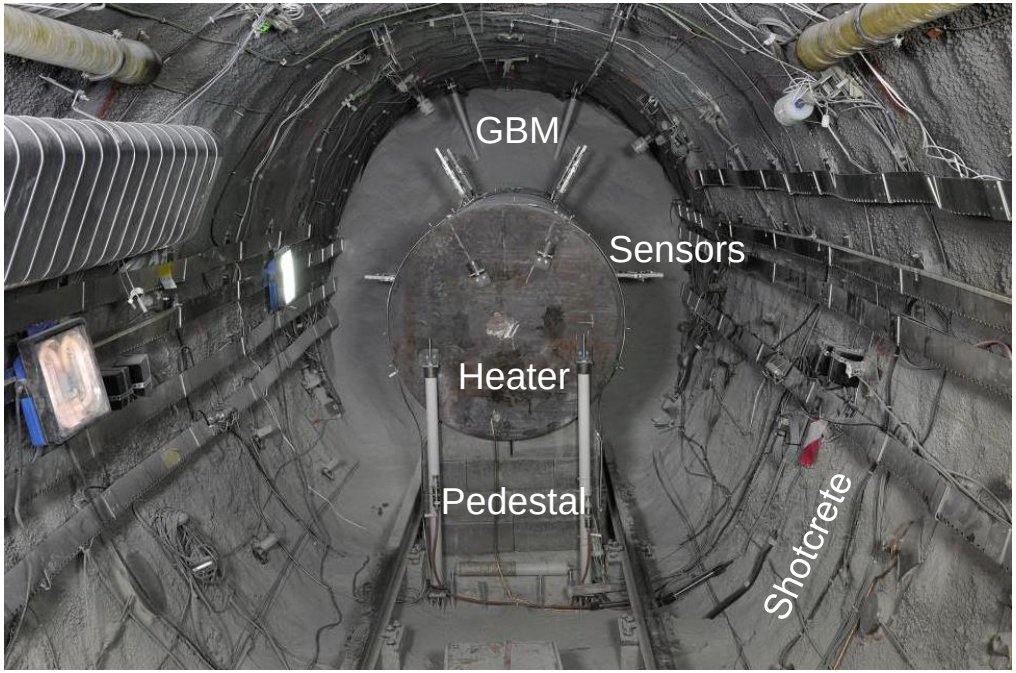
The FE experiment. Objectives.

- **Thanks to the experimental FE partners in the Mont Terri Consortium:**

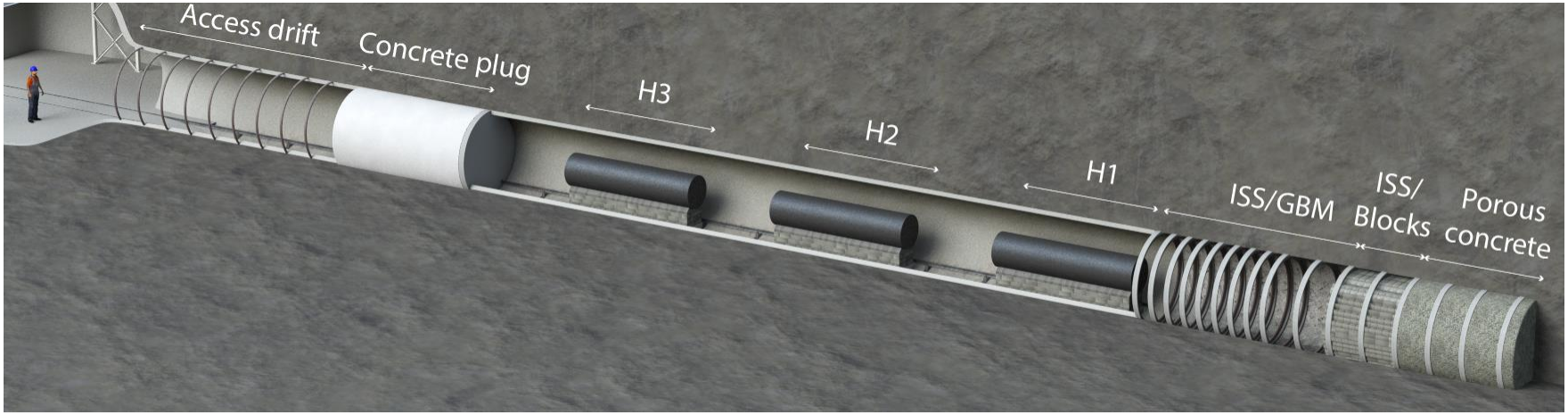
Nagra (Switzerland)	NWMO (Canada)	RWM (UK)	ANDRA (France)	DOE (USA)	BGR (Germany)	GRS (Germany)	FANC (Belgium)
FE-M / FE-G				**FE-M**			

- **Main goal:** investigate SF/HLW repository-induced THM coupled effects on the host rock and the backfill material at 1:1 scale and to validate the technical readiness of existing THM modelling software.
- **Other goals:**
  - To verify the technical feasibility of constructing a repository tunnel using standard industrial equipment.
  - To optimise the bentonite buffer material production.
  - To investigate horizontal canister and buffer emplacement procedures at underground conditions.

The FE experiment. The layout in brief.



- 50m long, ~3m diameter.
- Block bentonite pedestals.
- 3 heaters. Dimensions ~ canisters.
  Thermal output 1350W each. 4 years of heating.
- Backfilling with GBM.
- Low-pH shotcrete (not at ISS).
- 955 sensors (T, ω, p, λ, u, gas, corrosion) +FO+geophysics. Overall, 90% still work.



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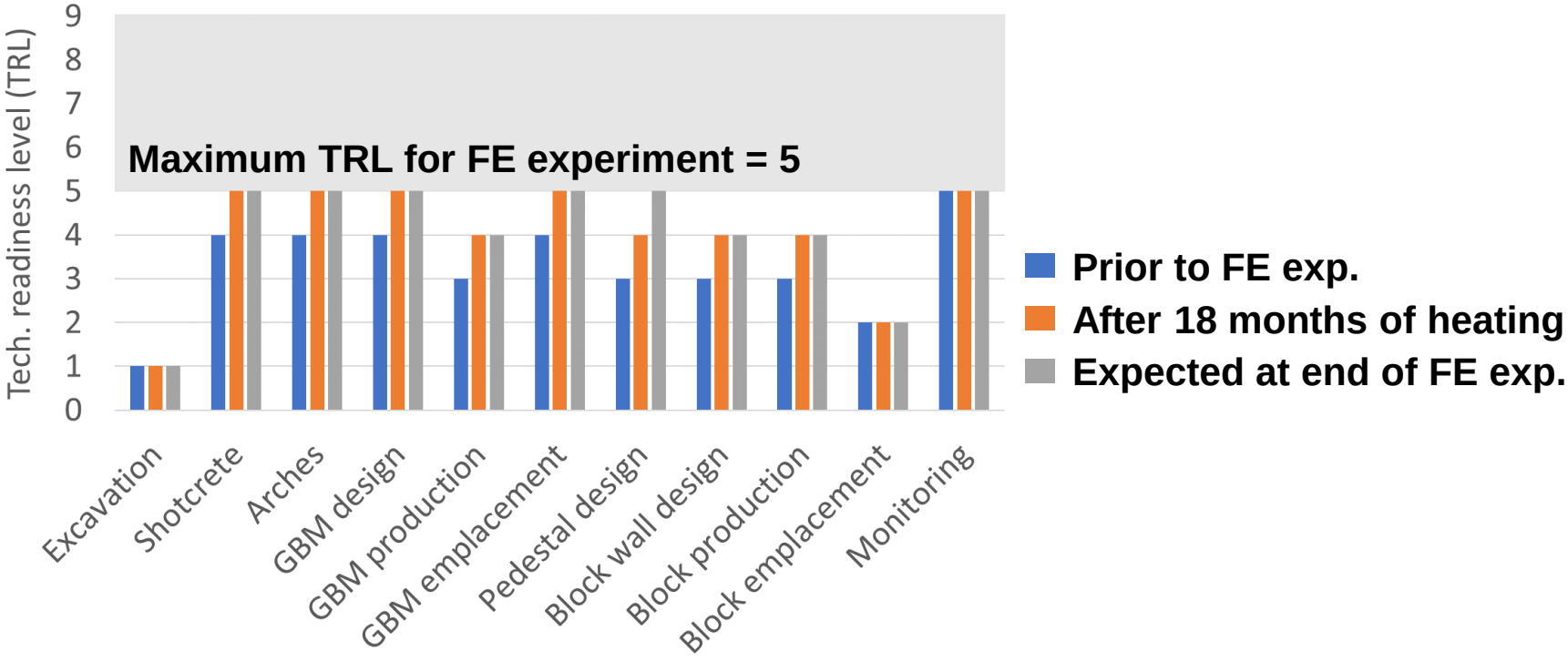
The FE experiment. Lessons learnt so far.

- **TRL:** Technical readiness level. From 1 to 9 (readiness low – technology proven through operation; Euratom Work Programme 2018).
- Maximum TRL for FE is 5 because:
  - the Opalinus Clay in Jura is more tectonised than in the candidate siting areas.
  - the FE Experiment is being used to develop requirements on the detailed design.



The FE-M project.

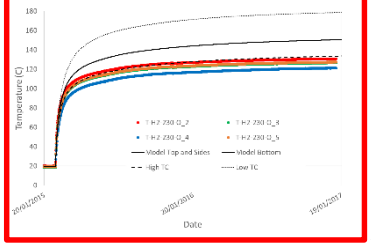
- **Goals of FE-M:** maintenance and monitoring of FE. 6 work packages
  - WP1: data acquisition (maintenance, alarm system, continuous heating, etc.)
  - WP2: In-situ characterization (thermal conductivity, TDR, etc.)
  - WP3: Geophysics: logging, seismics, radar, etc.
  - WP4: FE database (FEIS). Data archiving, documentation archiving, etc.
  - **WP5: Models and analysis.**
  - WP6: Laboratory experiments, literature study, etc.
- **Goals of WP5:** Analysis of collected data and modelling.
  - Confirmation of the completeness of the THM RIE framework.
  - Verification of existing software packages/ validation of THM models.
  - Calibration of parameters of THM models.
  - Decision-making for heating strategy and safety-related issues.
- Task force organized by Nagra. 2 appointed modelling teams (UPC/CIMNE and EPFL). Partners can appoint modelling teams.

The FE experiment. Modelling.

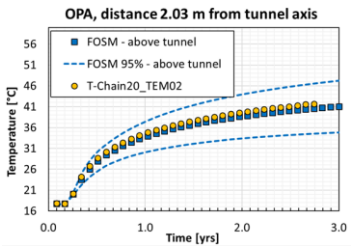
- Previous experiments and modelling exercises are valuable

HE-C	2002-2004	Vertical heating test with Ca bentonite blocks	Process understanding & 1st model
HE-D	2004-2005	Small scale hor. heating test without bentonite	Calibration of THM parameters of OPA
HE-E	2011-2014	1:2 horiz. heating test with bentonite pellets	Check THM parameters of OPA; Calibration of THM parameters of GBM
FE	2014	1:1 horiz. heating test with bentonite pellets	**Blind predictions**
FE-M	2018		RIE far field

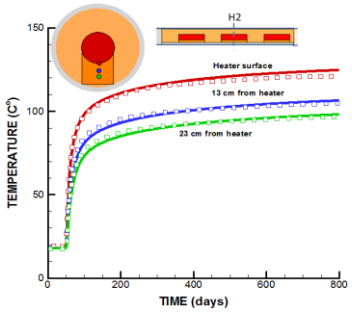
Quintessa



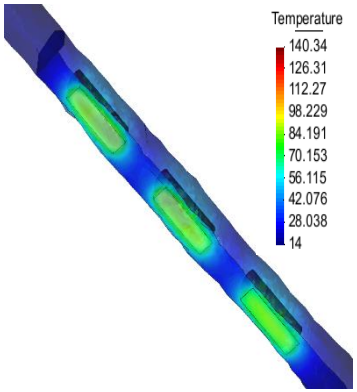
Intera



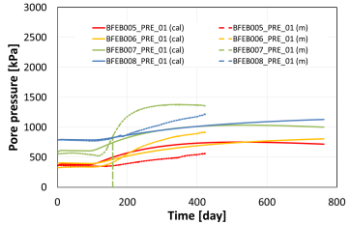
LBNL



GRS



BGR



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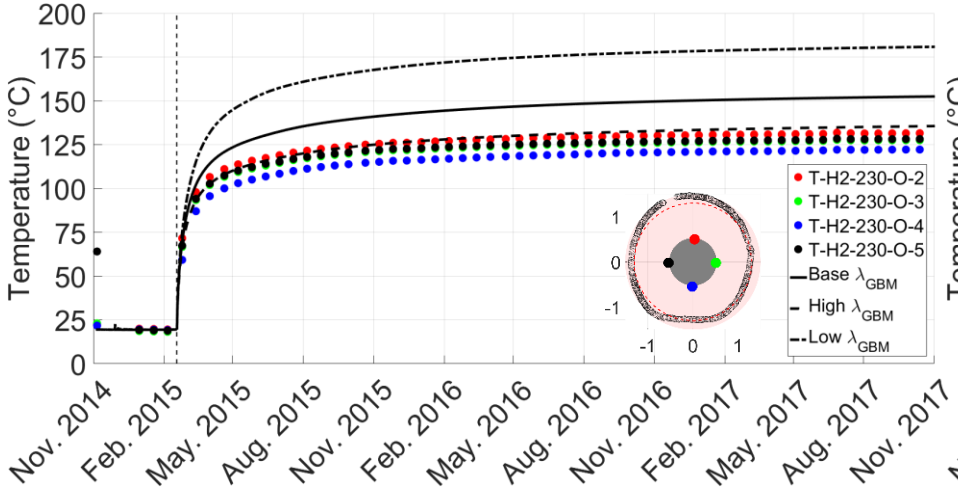
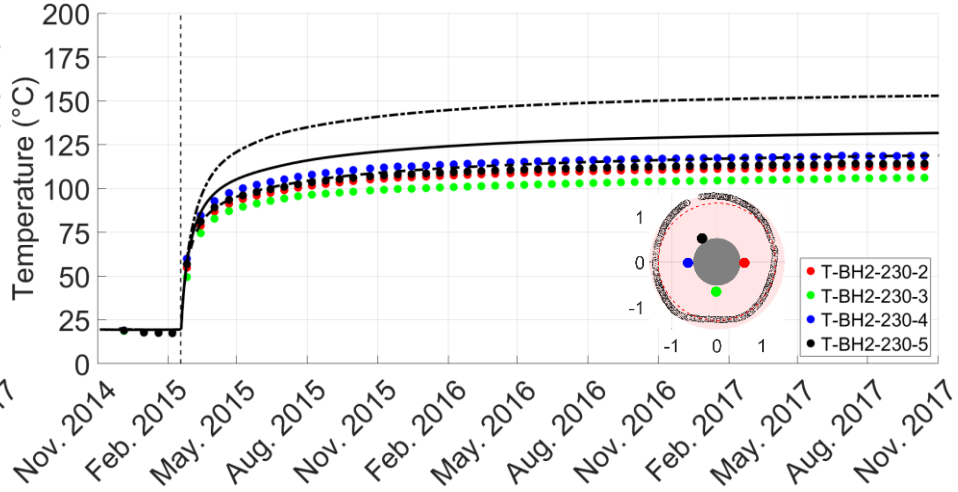
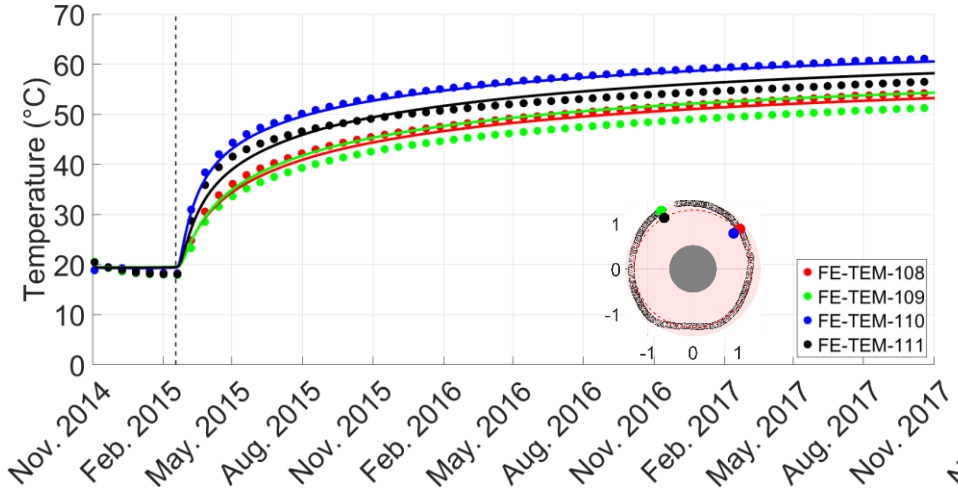
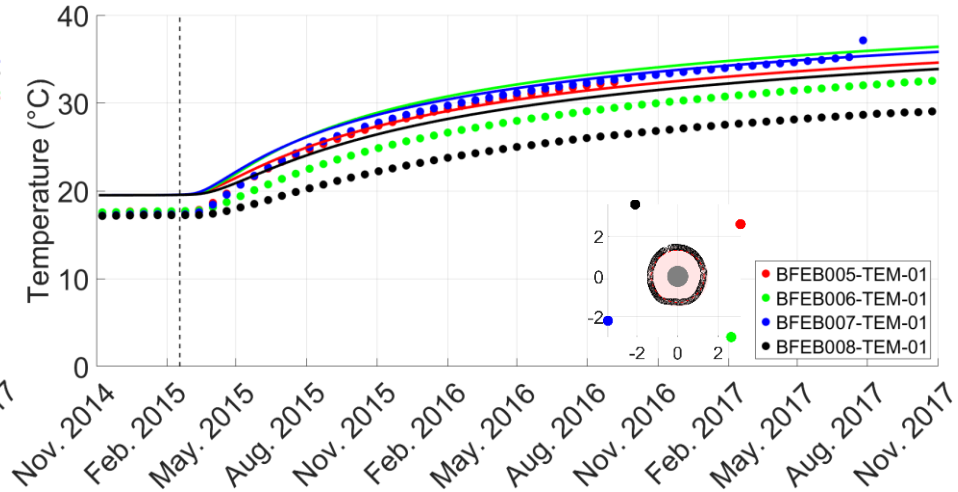
The FE experiment. Blind predictions. Heater H2









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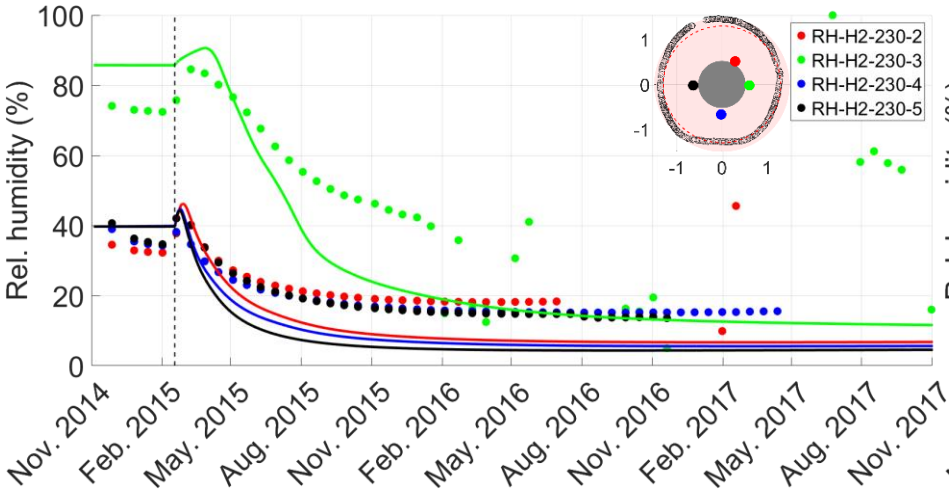
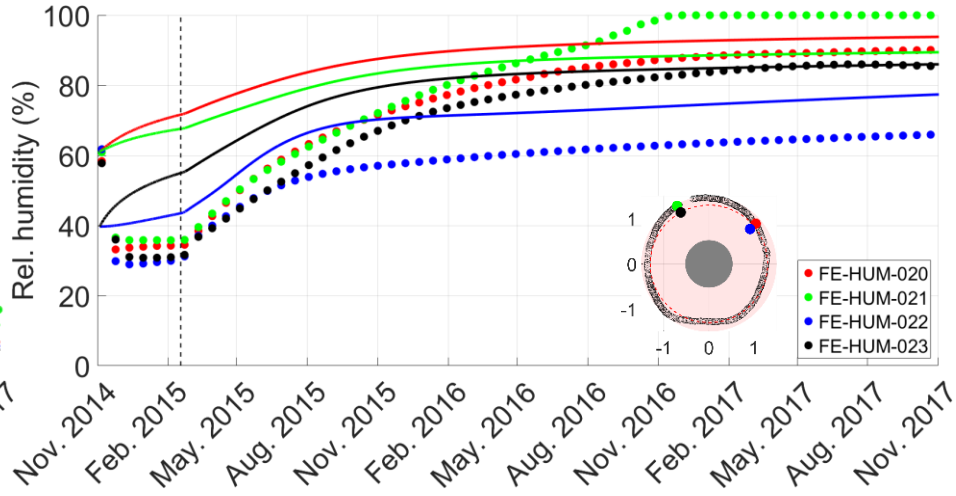
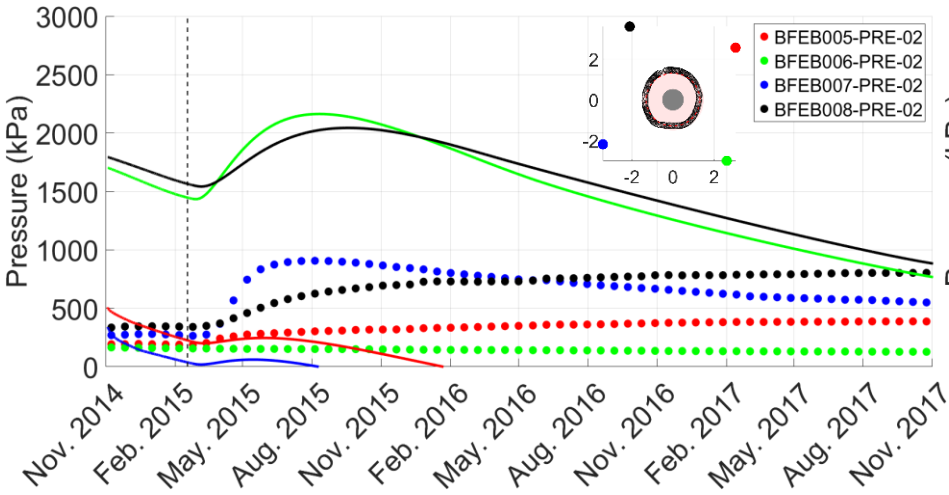
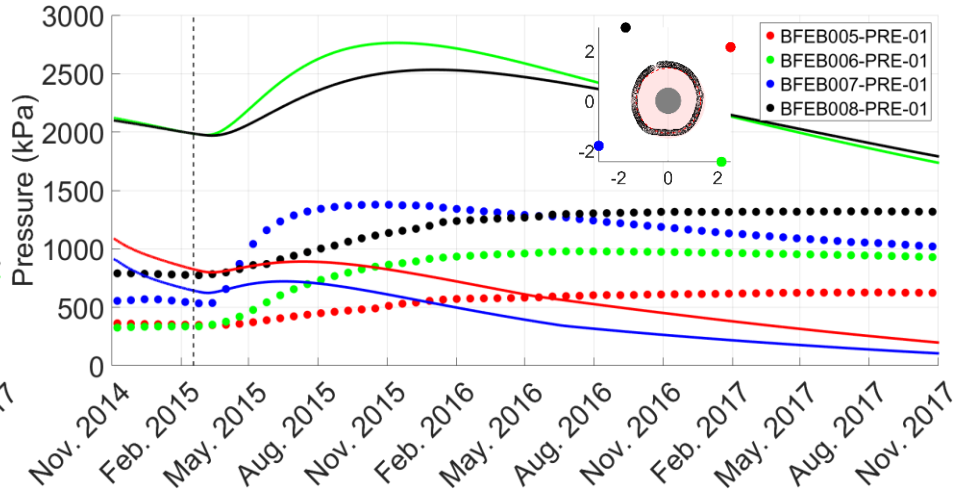
The FE experiment. Blind predictions. Heater H2.









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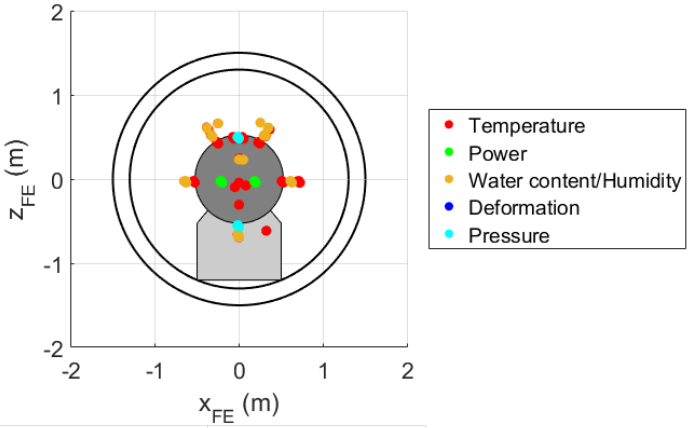
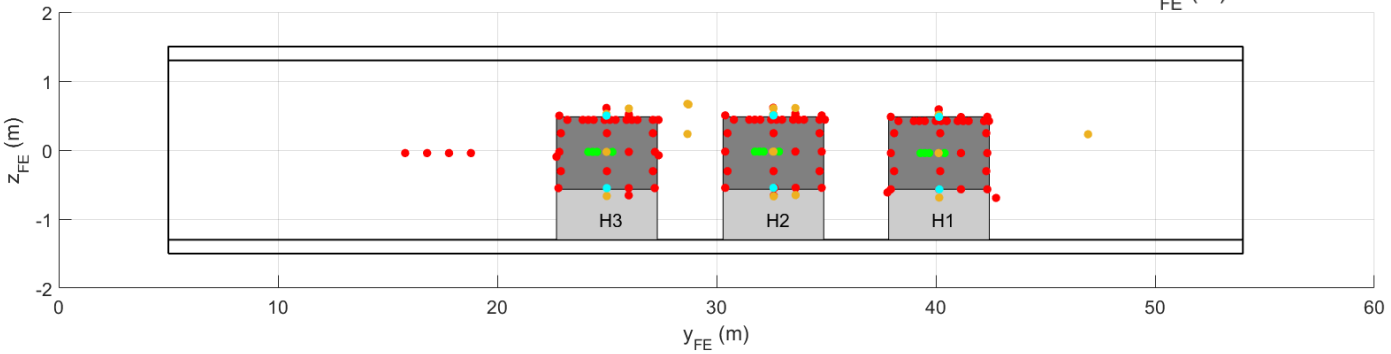
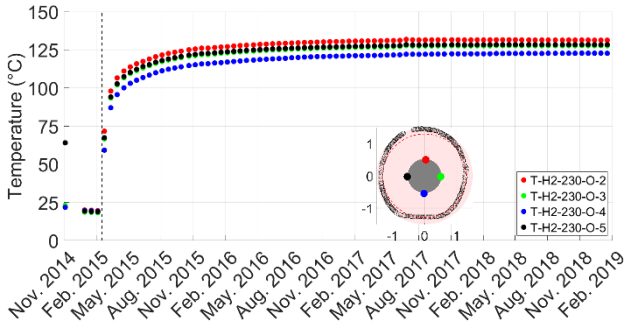
The FE experiment. Data collection. Heaters.

- Heaters (d<20cm): 199 sensors.
  - Temperature (139; 89.9%)
  - Water content (23; 39.1%)
  - Total pressure (6; 0%)
  - Power (12; 100%)
  - Deformation (19; 78.9%)

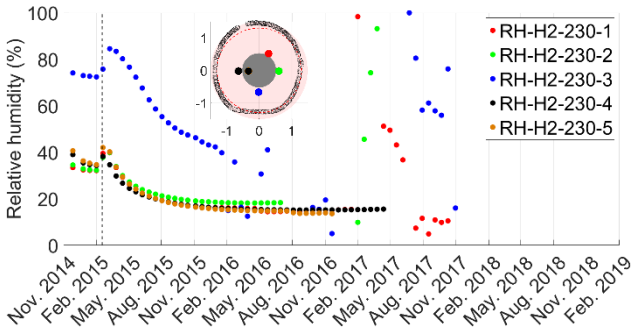




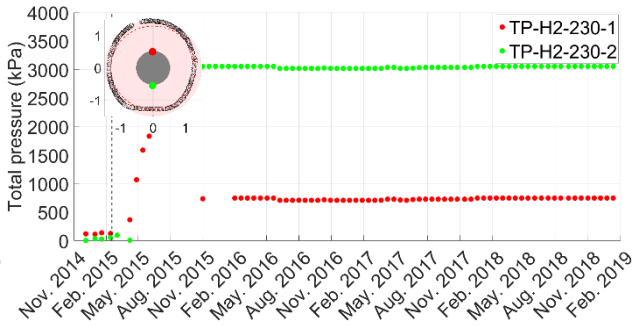
Temperature



Relative humidity



Total pressure



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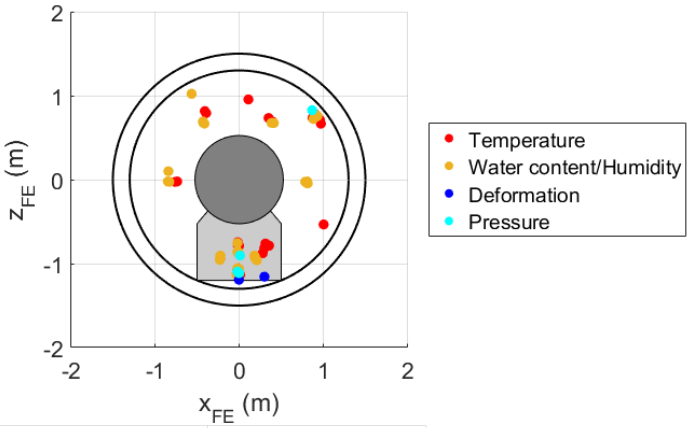
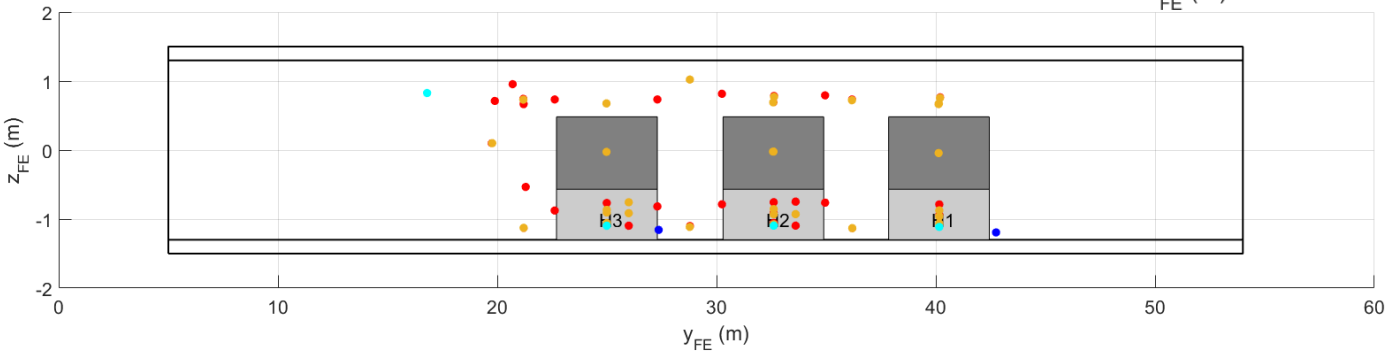
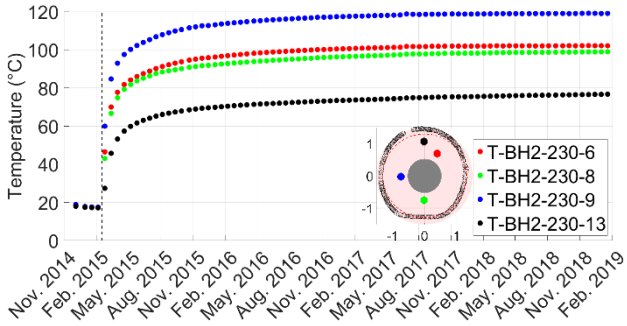
The FE experiment. Data collection. Bentonite.

- GBM and pedestals: 136 sensors.
  - Temperature (87; 79.3%)
  - Water content (46; 54.3%)
  - Total pressure (3; 33.3%)

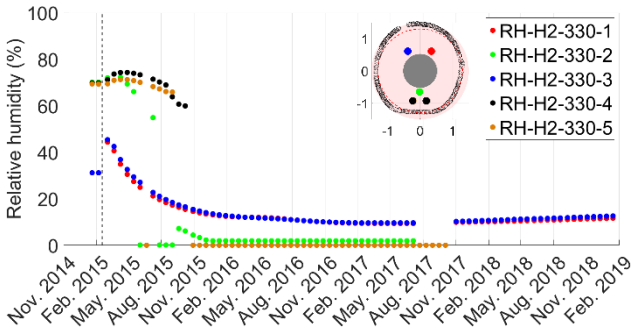




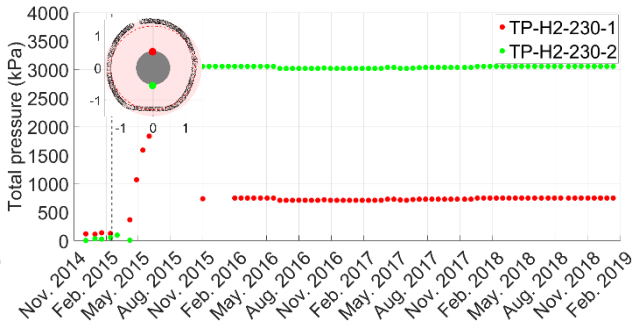
Temperature



Relative humidity



Total pressure



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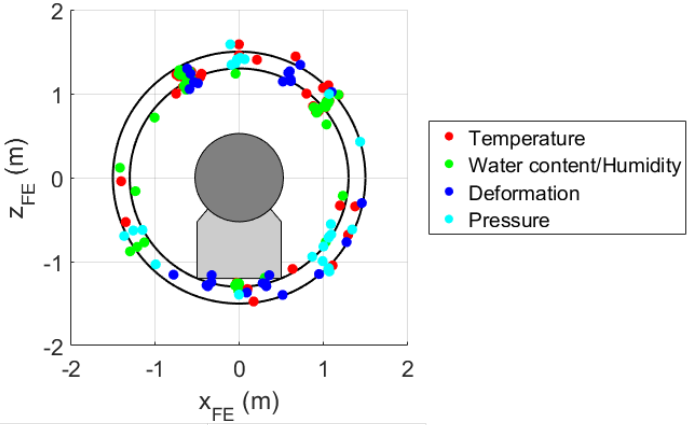
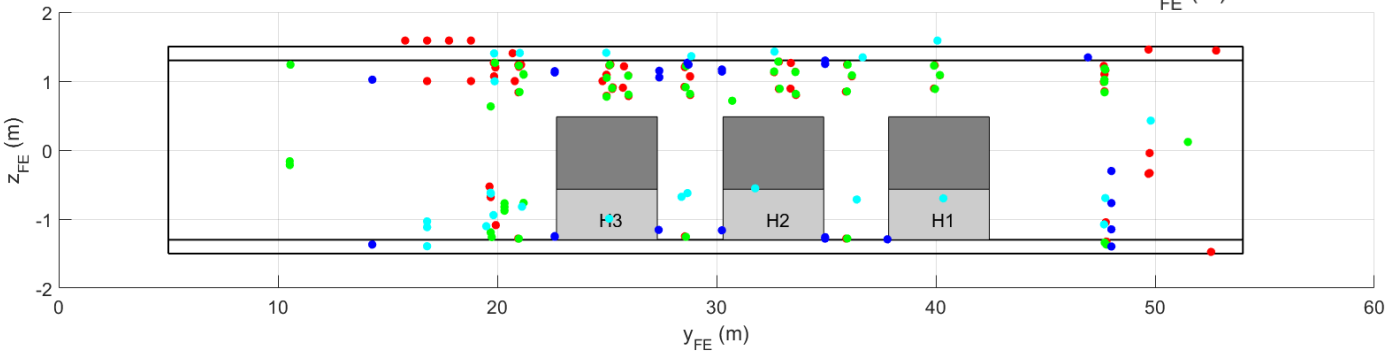
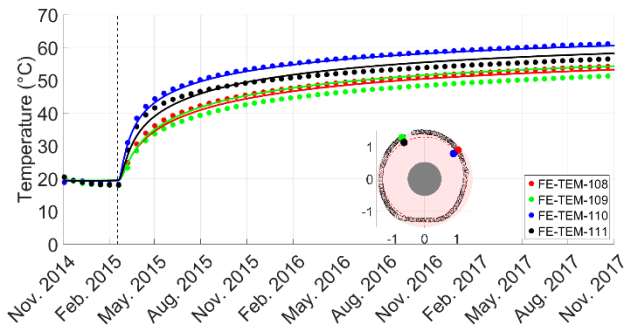
The FE experiment. Data collection. Tunnel wall.

- Tunnel wall (d<10cm): 231 sensors.
  - Temperature (136; 93%)
  - Water content (56; 98%)
  - Total pressure(18; 89%)
  - Gas (6; 100%)
  - Thermal conductivity (15; 93%)

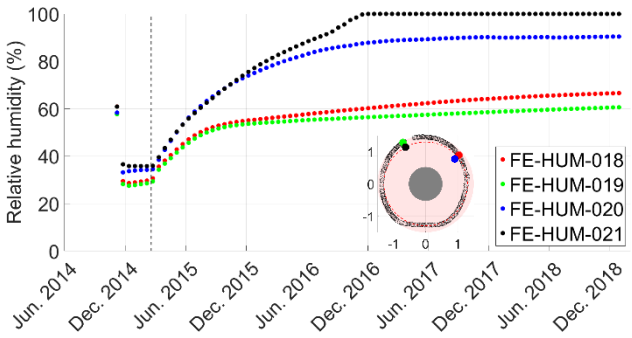




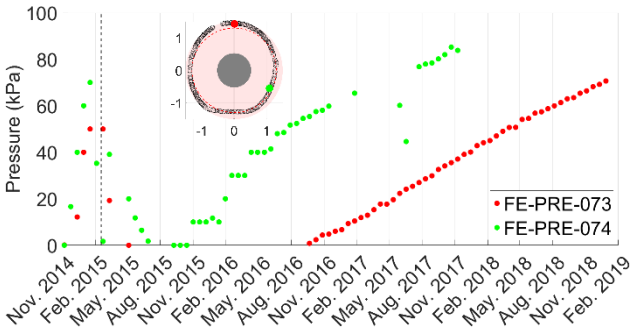
Temperature



Relative humidity



Total pressure



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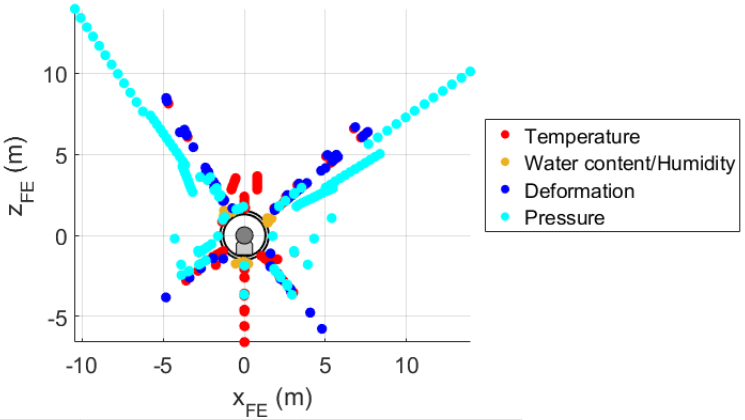
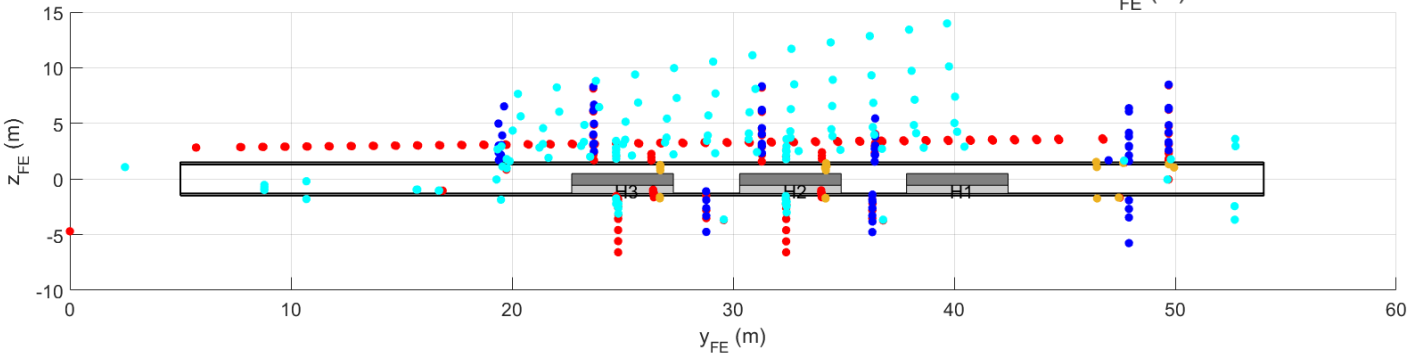
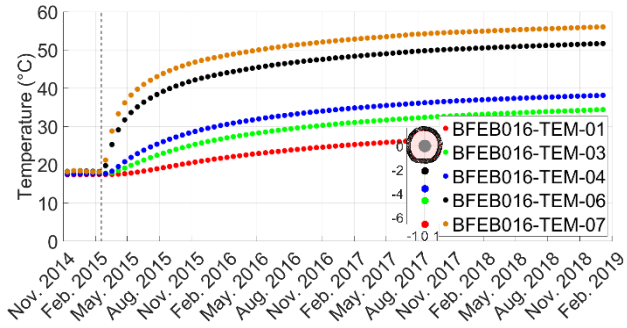
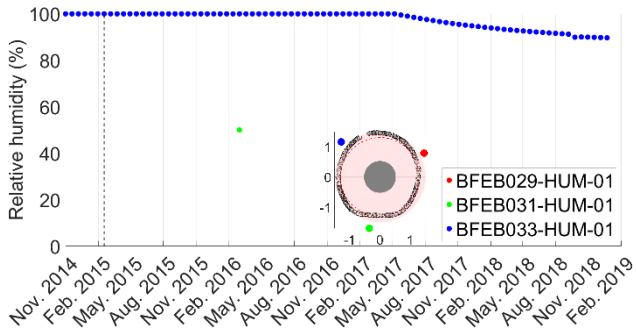
The FE experiment. Data collection. OPA.

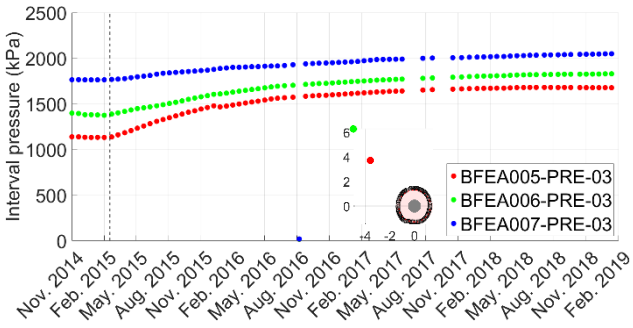
- Opalinus Clay: 534 sensors.
  - Temperature (225; 90.2%)
  - Water content (69; 84.1%)
  - Total pressure (116; 97.4%)
  - Deformation (124; 100%)











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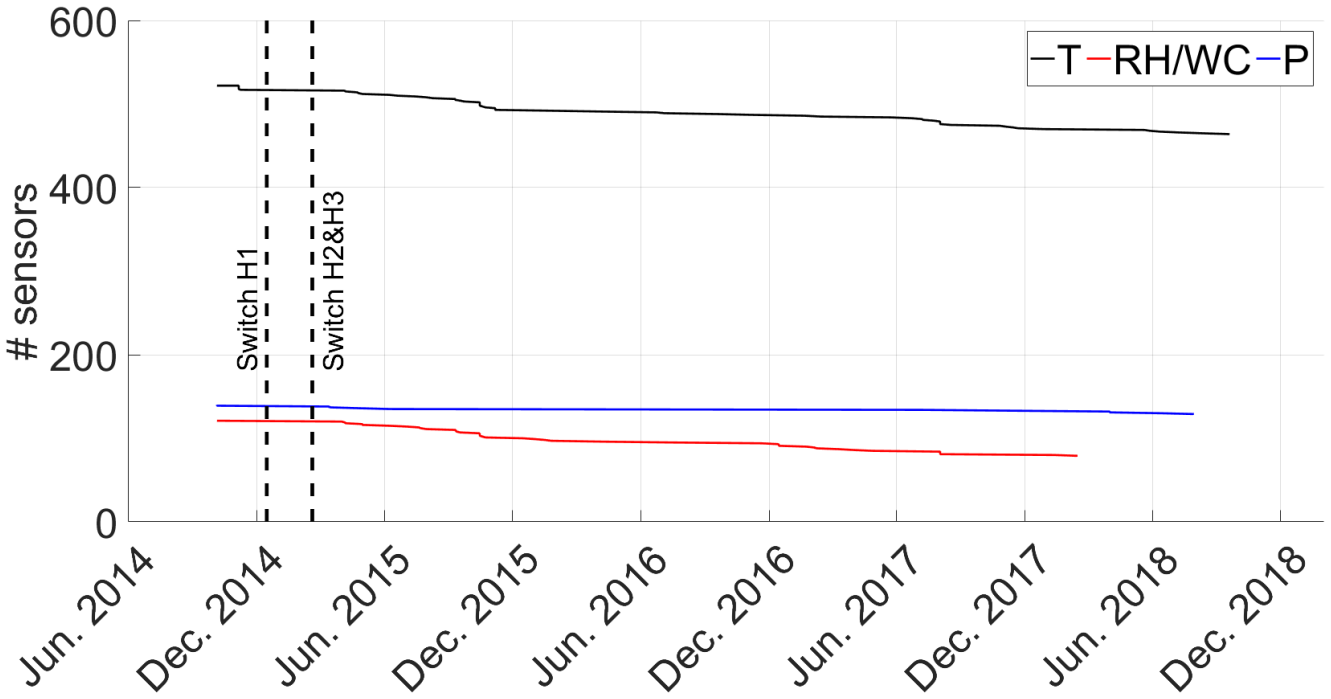
The FE experiment. Data collection. Overview.

- **Temperature**: 523. Not working: 61. Operative rate: 88.3%.
- **Rel. hum./water content**: 120. Not working: 43. Operative rate: 64.2%.

  Failure mainly close to heater (high T) or at wet spots at tunnel wall.
- **Pressure: 141.** Not working: 13. Operative rate: 90.8%.



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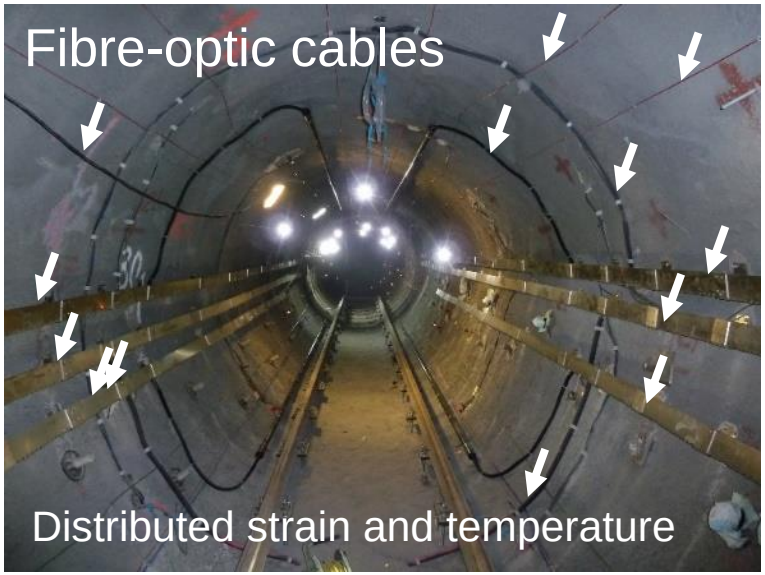
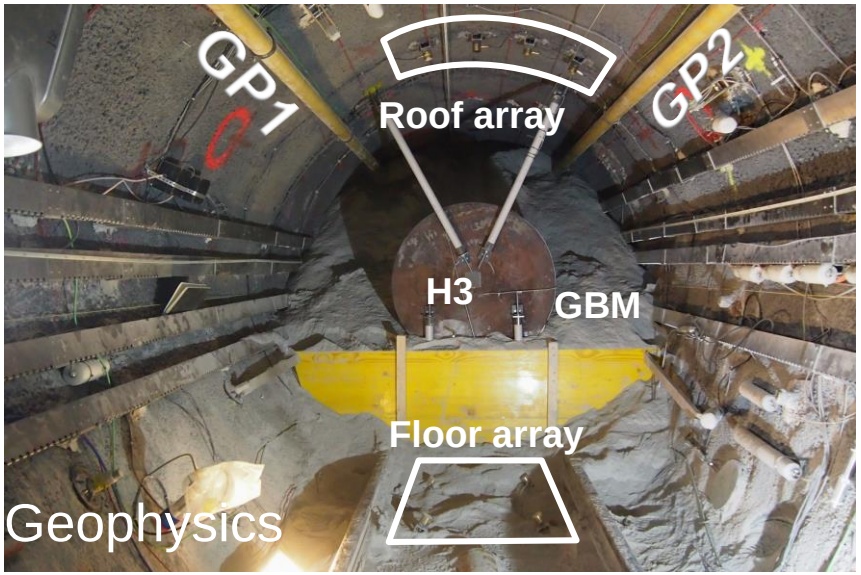
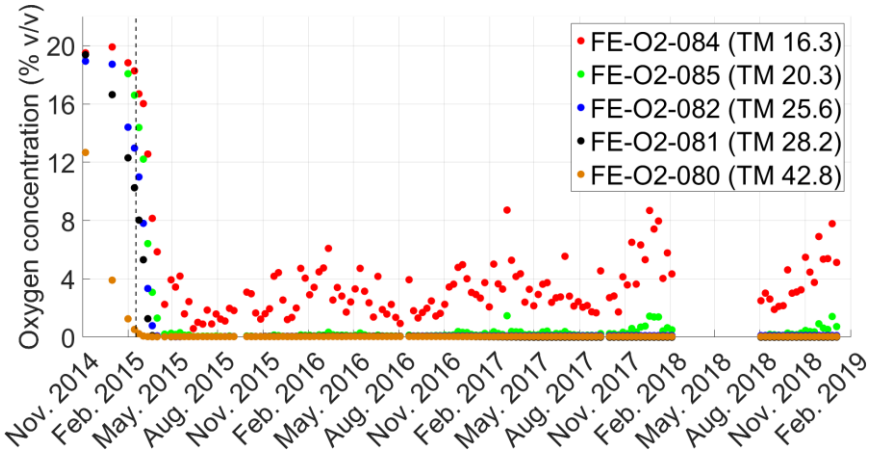
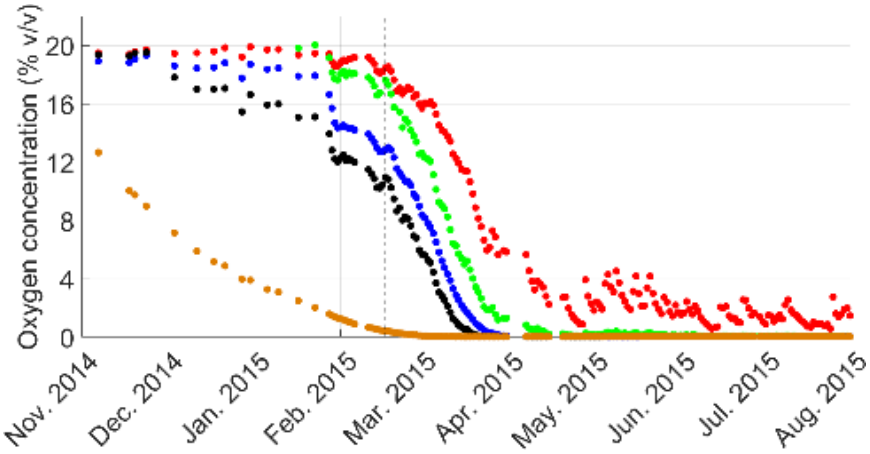
The FE experiment. Data collection. Others.





- FE-G: Oxygen concentration drops to ~0% 2-3 months after backfilling.





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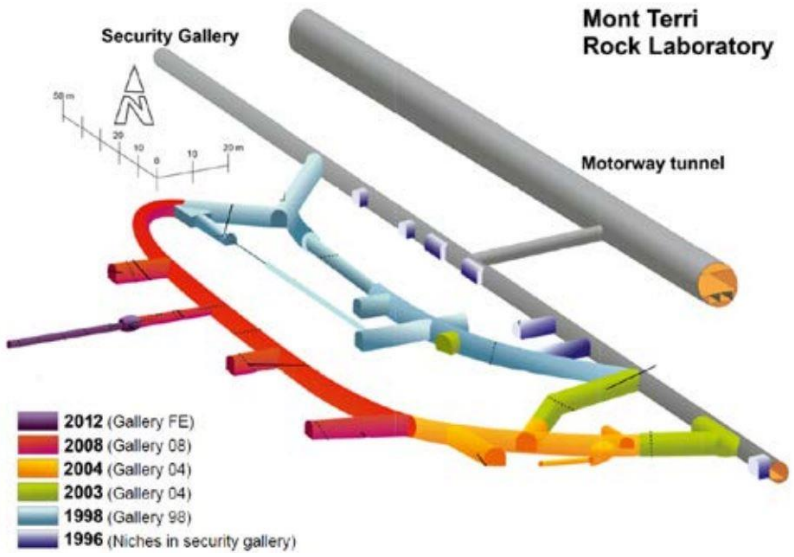
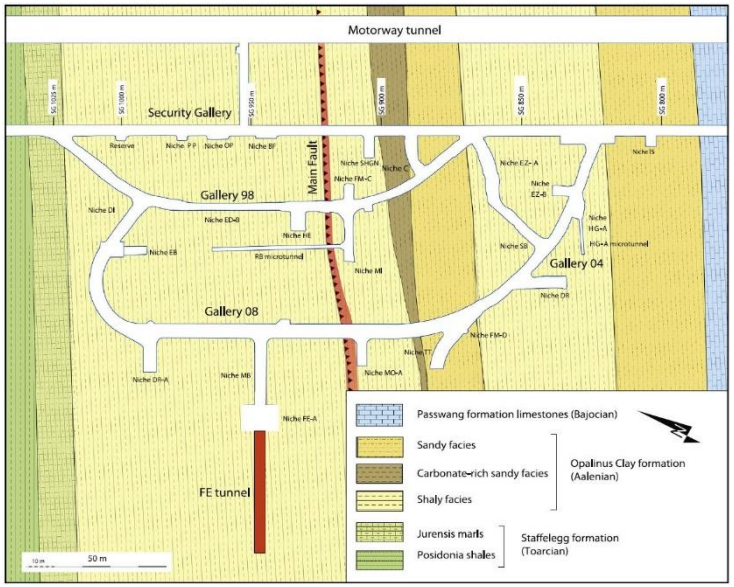
Key points

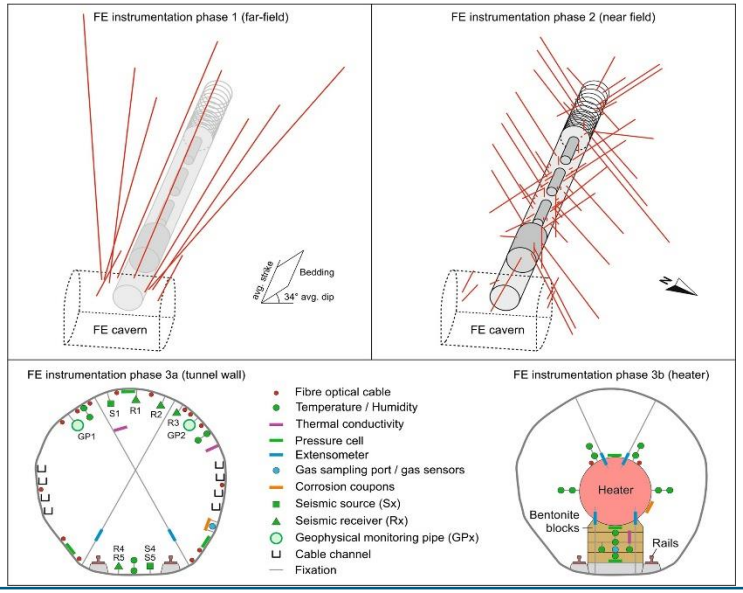
- FE is a valuable experiment for ascertaining TRL of constructive aspects and available modelling tools.
- Instrumentation works fine (90%).
- Other on-going activities include:
  - distributed temperature and strain analysis (fiber optics).
  - continued and redundant geophysics monitoring.
  - gas monitoring (FE-G).
  - lab experiments.
  - modelling.
- FE Modelling Task Force set up to assess the completeness of the THM RIE framework.

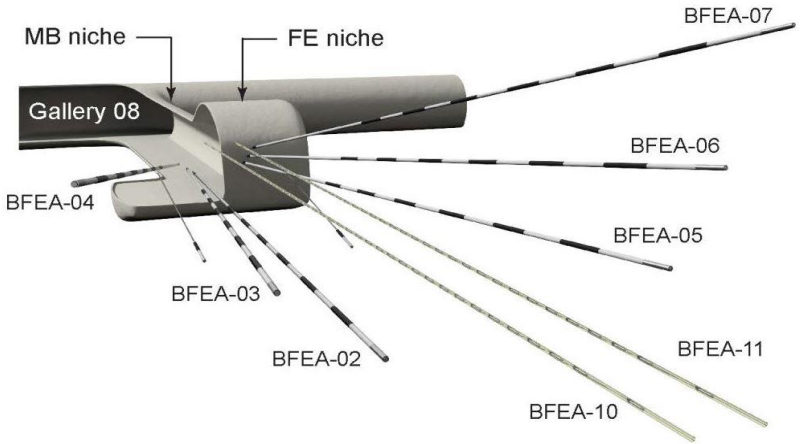
Nagra (Switzerland) | NWMO (Canada) | RWM (UK) | ANDRA (France) | DOE (USA) | BGR (Germany) | GRS (Germany) | FANC (Belgium)

Overall layout









45m long boreholes

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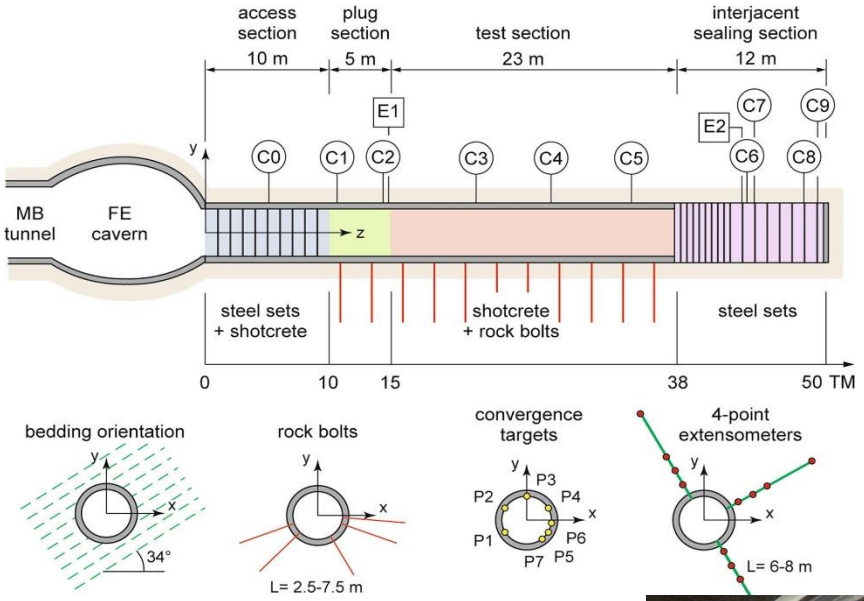
Tunnel support. The ISS



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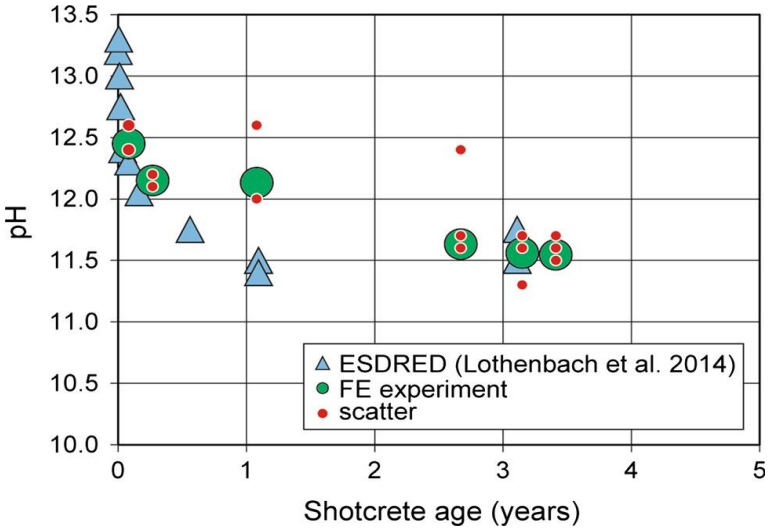
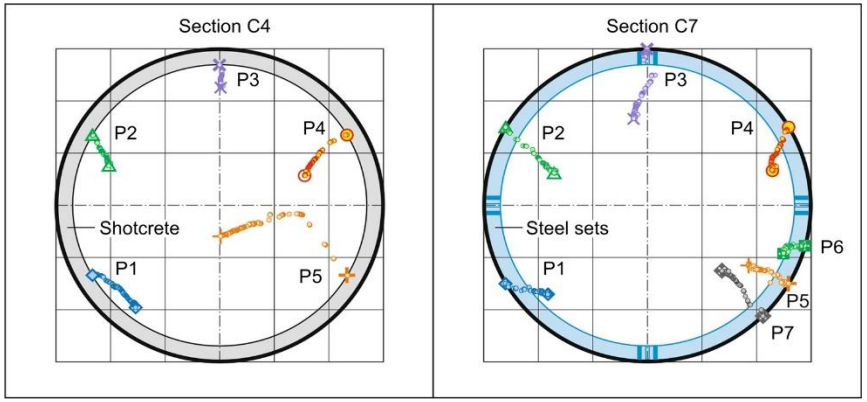
Shotcrete



Component / property	Quantity / value
Water (w)	173 kg/m^3
Cement (c) (CEM I 42.5 R-SE)	270 kg/m^3
Silica fume (s) (Degussa)	180 kg/m^3
Superplasticizer (Mapei)	0.41 kg/m^3
Limestone aggregates (< 8 mm)	1661 kg/m^3
Air content	4.5 vol-%
Theoretical density	2284 kg/m^3
Water: cement ratio	0.64
Water: cement and silica ratio	0.38

Property	Quantity / value
Total porosity	23.1 vol-%
Density	2063 kg/m^3
Free water content	4.7 vol-%
Water permeability	1.15 x 10^{-17} m^2
Thermal conductivity	1.71 W/mK
Uniaxial compressive strength	42.4 MPa (28 days) 50.4 MPa (90 days)



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GBM specifications

Safety-relevant attribute	Contribution to provision of safety function or another attribute	Preferred Value	Treatment in FE Experiment
Low hydraulic conductivity	Attenuation safety function of buffer, by ensuring diffusive transport	$K < 10^{-11}$ m/s for buffer around canister	At the onset of the Experiment, it was recognised that the required hydraulic conductivity could be achieved through production and emplacement of bentonite blocks and GBM with sufficient density (Garitte et al. 2017)
Chemical retention of radionuclides	Attenuation safety function of buffer, by retarding transport from the buffer	No quantitative criterion[1], strong sorption is favoured	Use of bentonite meets this requirement, as discussed in Leupin et al. (2014)
Sufficient density	Attenuation safety function of buffer, by preventing colloid transport	$\rho_d > 1.45$ g/cm^3 [2]	Measured during production of blocks and GBM, and emplacement of GBM in FE tunnel
Sufficient swelling pressure (P_s)	Attenuation safety function of rock, by providing mechanical stabilisation of rooms , and hence avoiding significant extension of EDZ	0.2 MPa < Ps < minimum principal stress	At the onset of the Experiment, it was recognised that the required swelling pressure could be achieved through production and emplacement of bentonite blocks and GBM with sufficient density (Garitte et al. 2017)
Mechanical support	Safety function of canister, by ensuring it is surrounded by a protective layer of buffer (stress buffering)	Buffer must be sufficiently viscous to avoid canister sinking[1]	The mechanical performance of the bentonite block pedestal was monitored using displacement sensors
Sufficient gas transport capacity	Attenuation safety function of buffer, by ensuring that gas can migrate without compromising the hydraulic barrier	No quantitative criterion[1]; less than the minimum principal stress	Not evaluated in the FE Experiment
Minimise microbial corrosion	Safety function of canister, by ensuring conditions favourable to slow corrosion	No quantitative criterion but higher densities are preferred to limit microbial activity[1]	At the onset of the Experiment, it was recognised that the required swelling pressure could be achieved through production and emplacement of bentonite blocks and GBM with sufficient density (Garitte et al. 2017)
Resistance to mineral transformation	Longevity of other safety-relevant attributes of buffer	No quantitative criterion[1]	Not evaluated in the FE Experiment
Mechanical support	Safety function of canister, by providing stress buffering	Not a required property	Not evaluated in the FE Experiment
Suitable heat conduction (Tc)	Safety function of canister, buffer and rock by ensuring favourable maximum temperature conditions	0.4 < Tc < 2 W/m K (for a specific thermal heat load of 1,500 W)	The thermal conductivity of the bentonite block pedestal and GBM was monitored using heat pulse sensors

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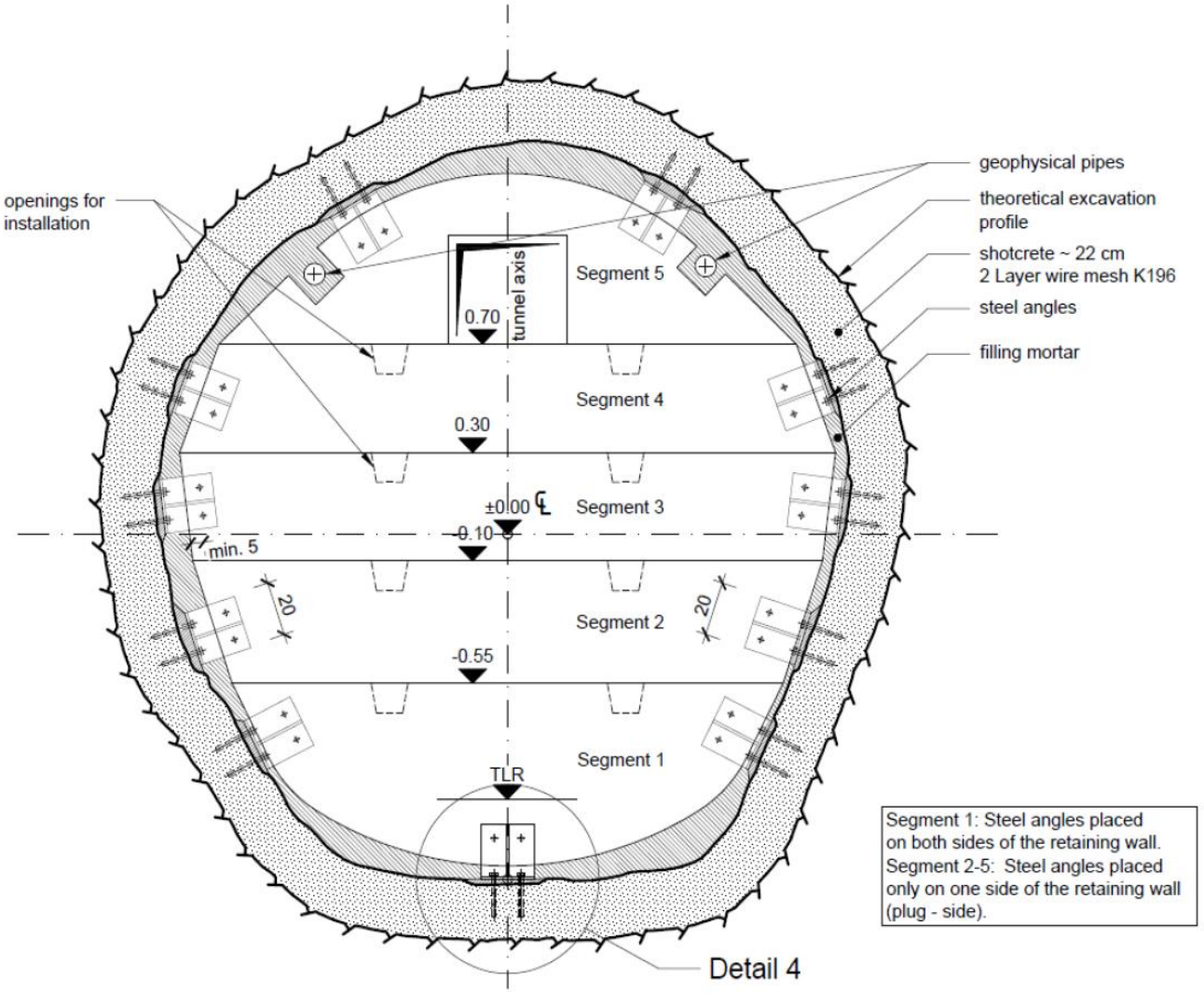
Concrete plug



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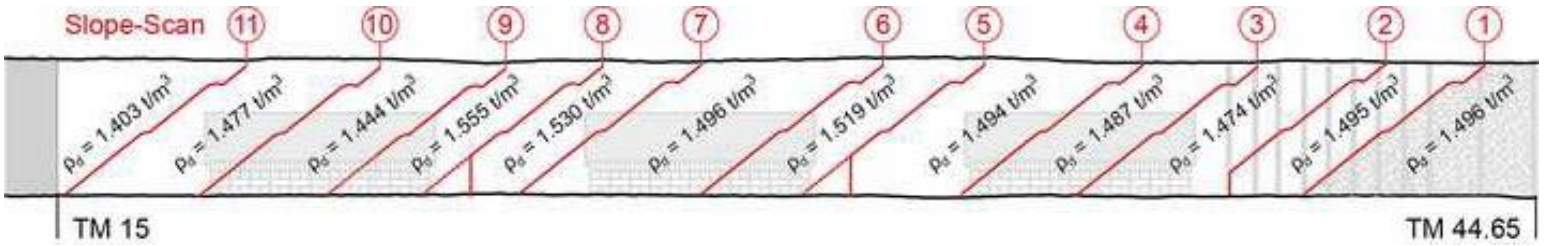
Bentonite block wall

2 m thickness

Backfilling machine



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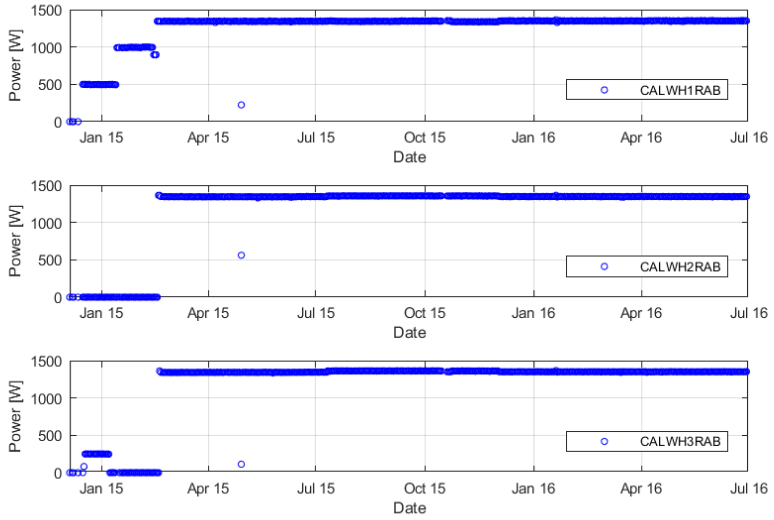
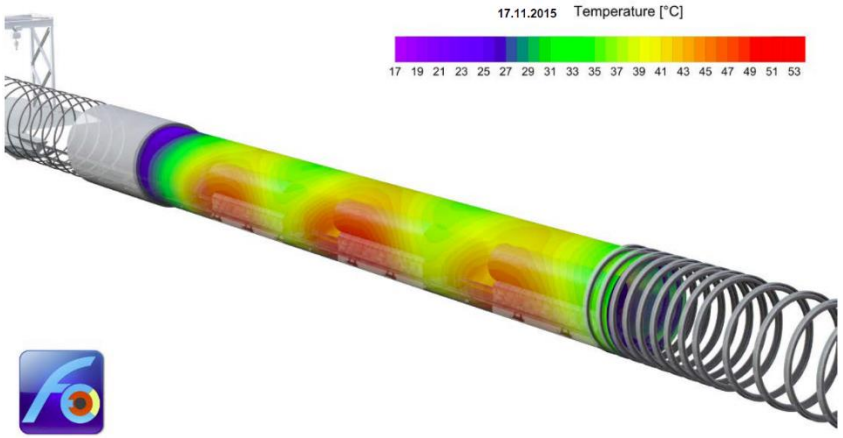
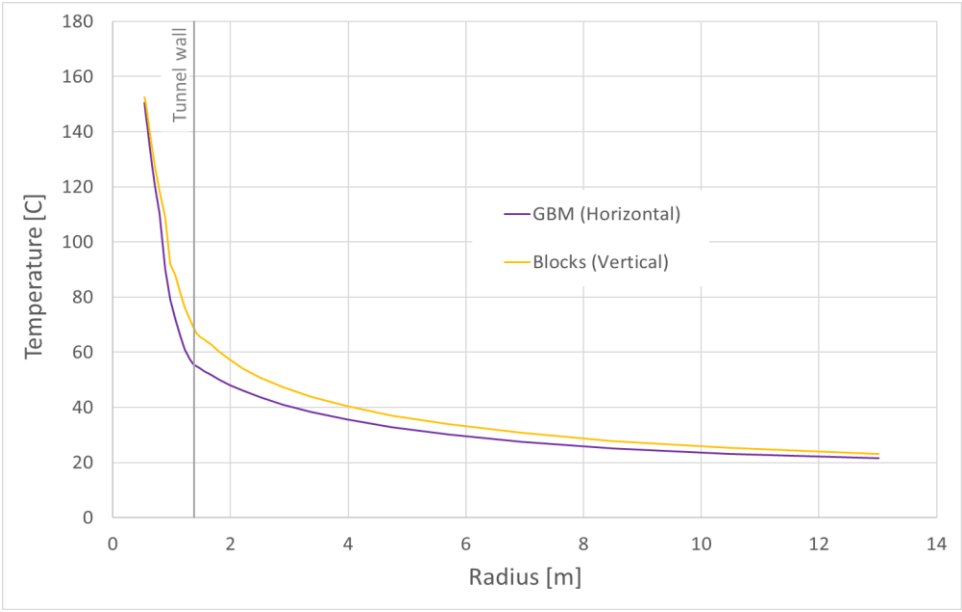
Heating sequence and T distribution





Time (years)	Heat Output MOX/UO2 (W)
0	1,500
3	1,450
10	1,330
30	1,080
100	696
300	422
1,000	177
3,000	68
10,000	39
30,000	14
100,000	3



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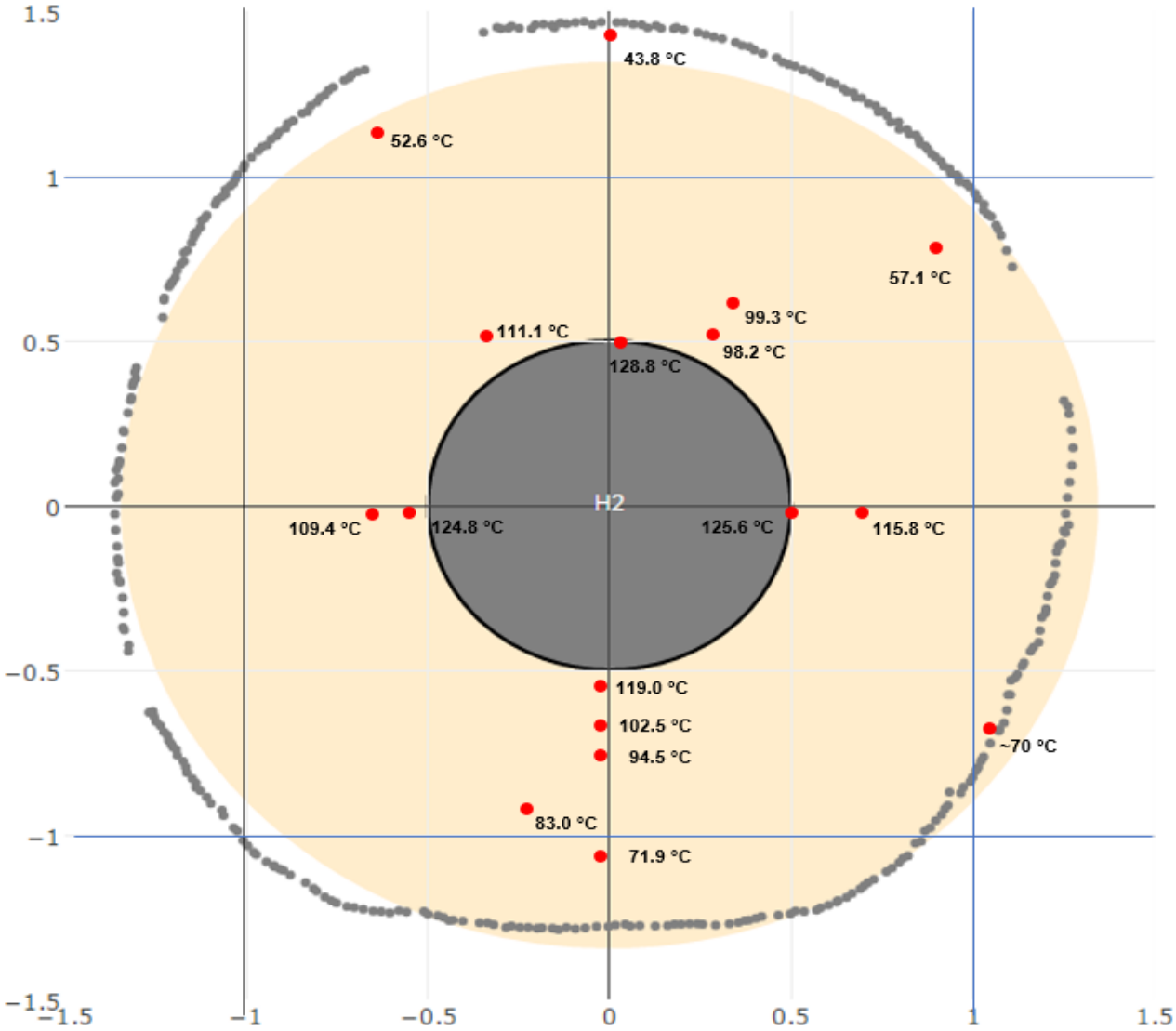
Temperature GBM and pedestals



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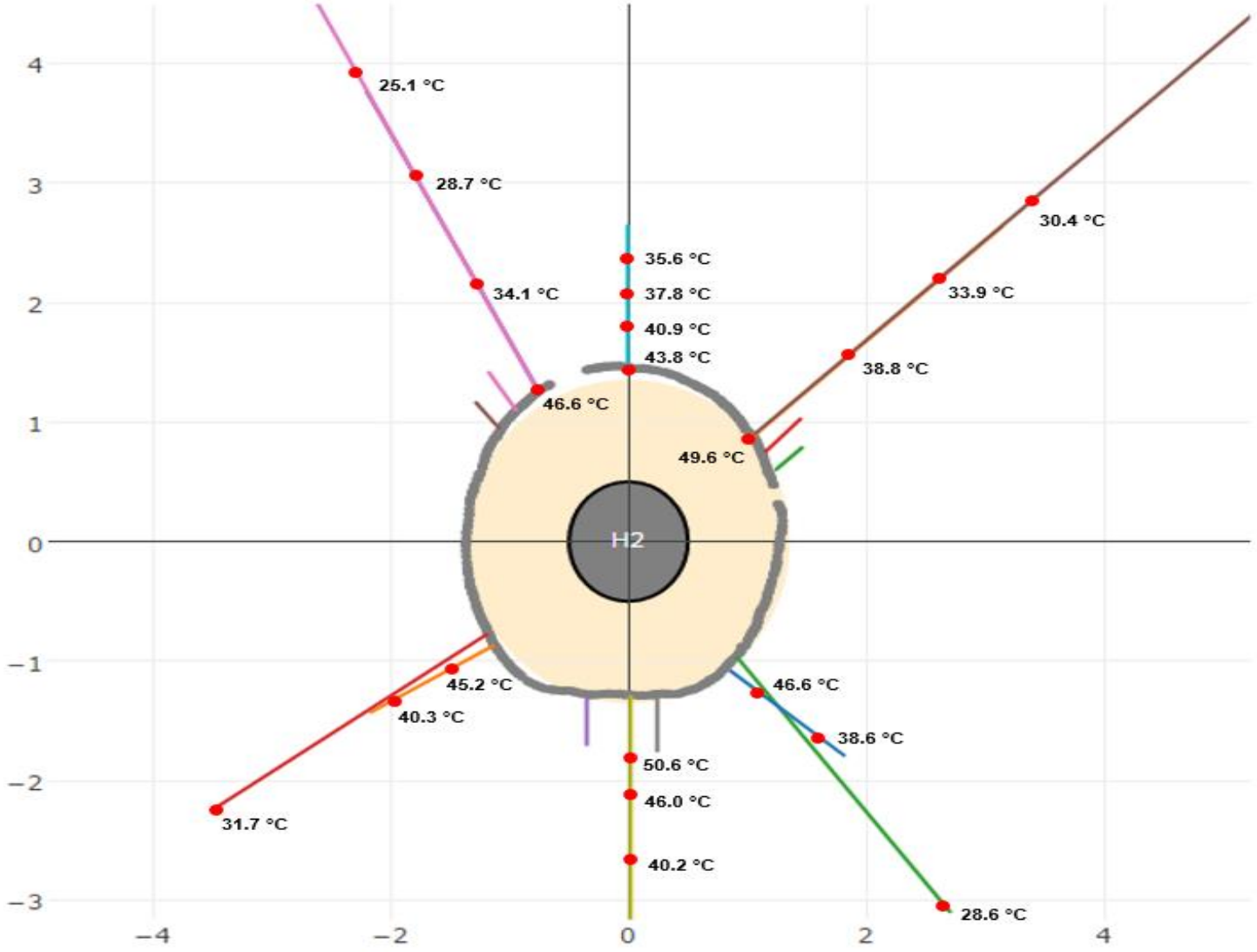
Temperature OPA



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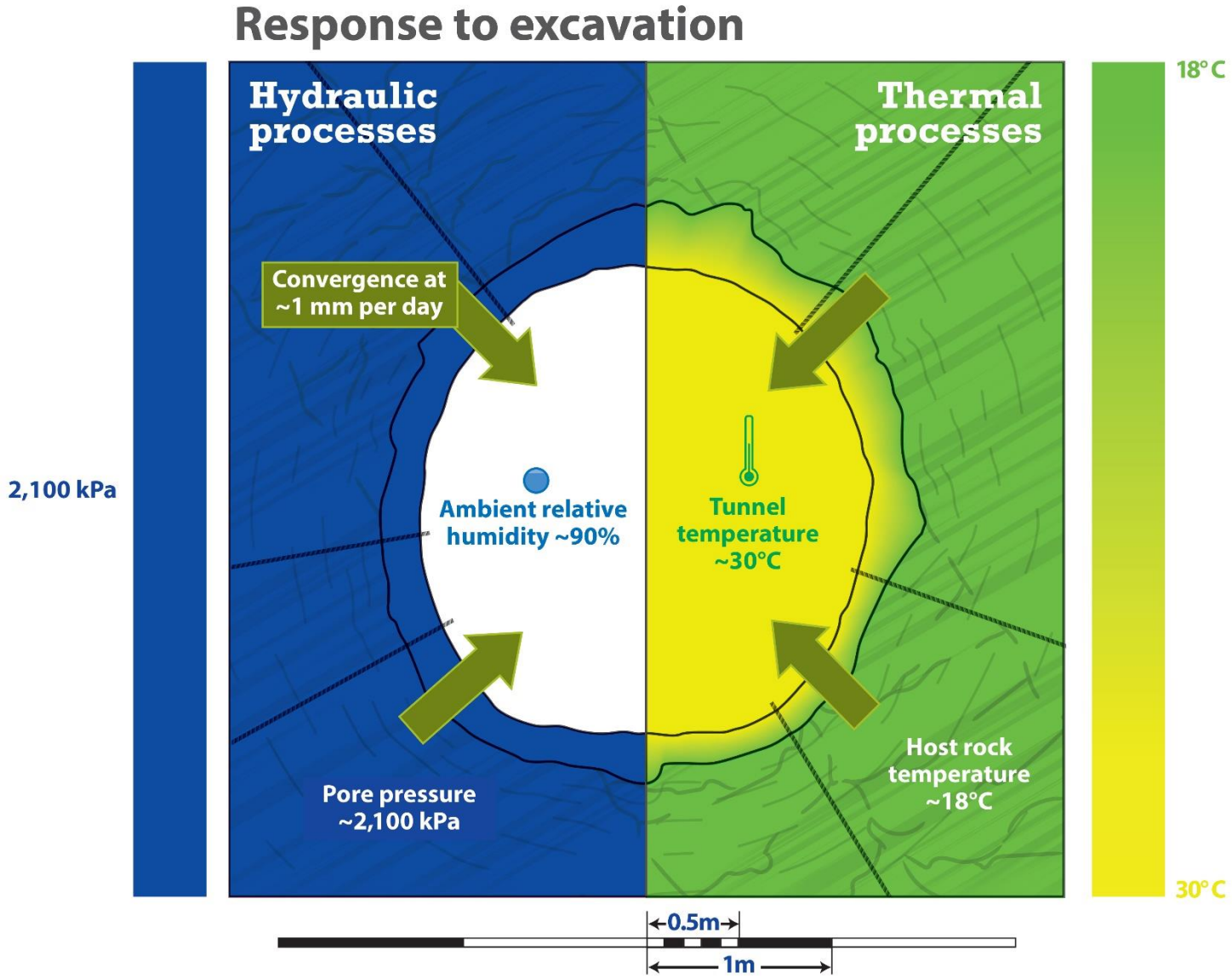
Processes



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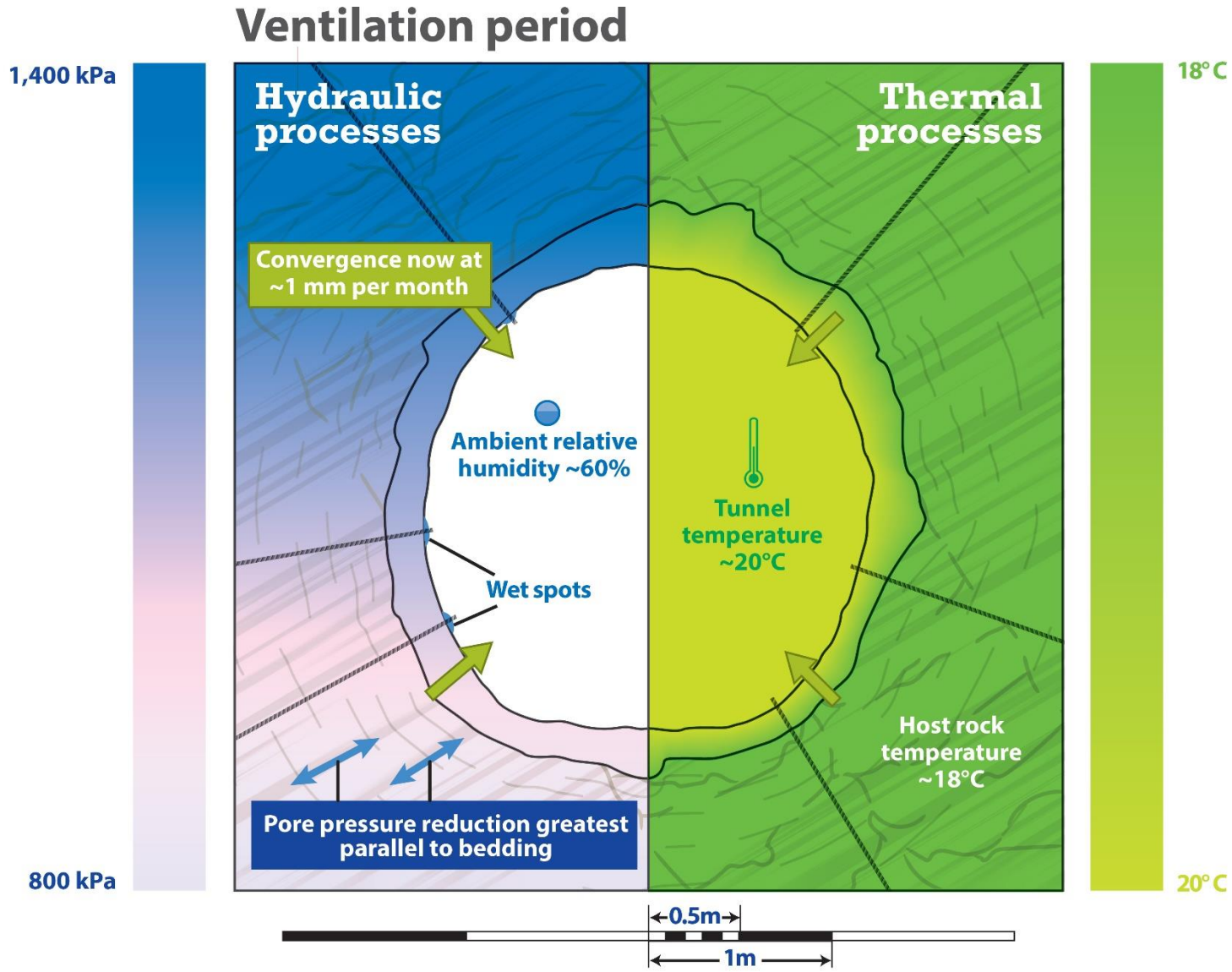

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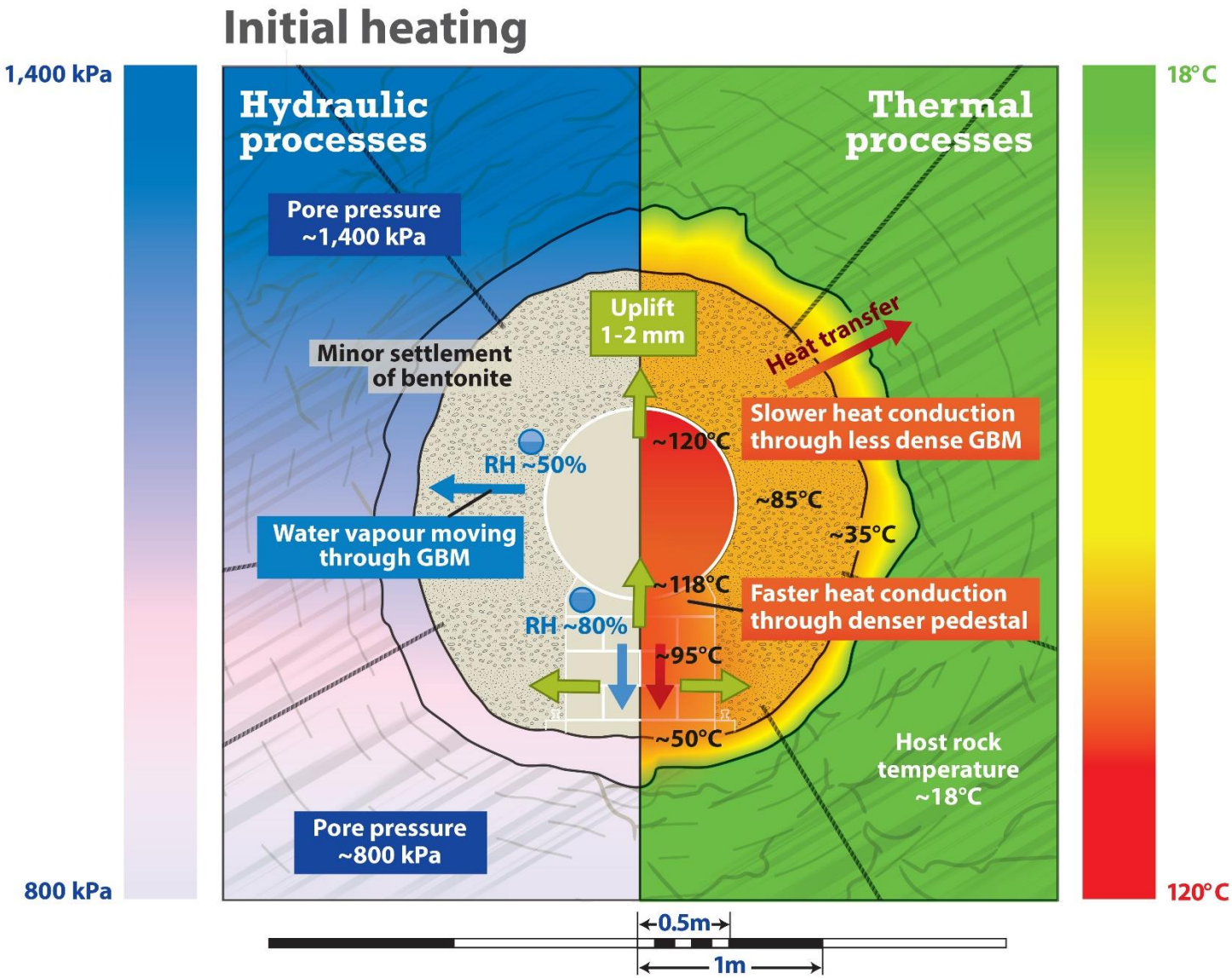

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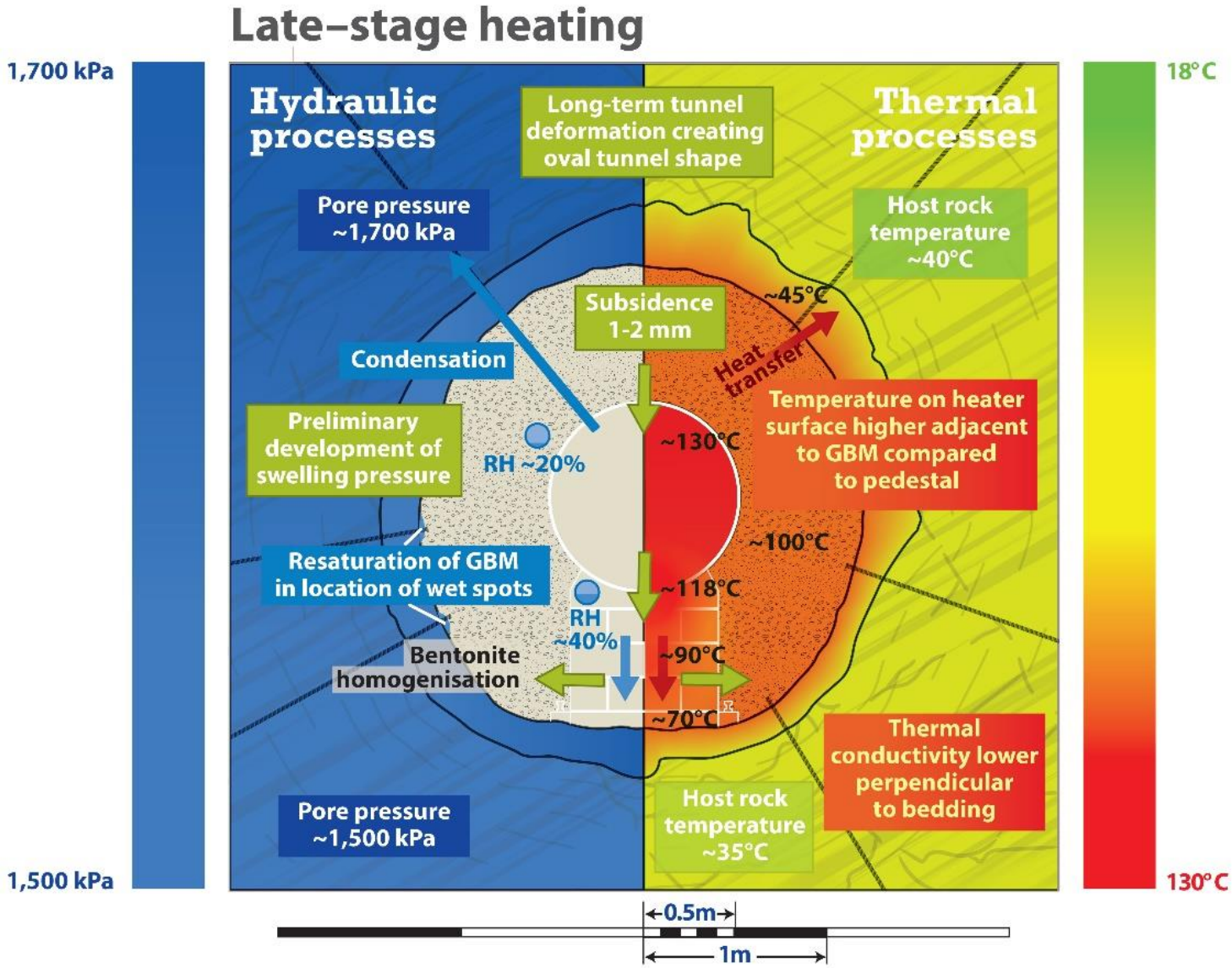
Processes



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